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TITLE REVIEW OF LONG-PULSE LASER DEVELOPMENT

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Abstract

A brief review of some present techniques to obtain long-pulse laser action in excimer discharge devices will be presented. An attempt will be made to point out the strengths and weaknesses of these techniques.

Introduction

There are a number of reasons why one would require longer laser pulses than those provided by present day commercial devices (20-30ns). The most important benefit is in transmitting more energy through optical fibers[1,2]. This use is strongly driven by possible medical applications relating to noninvasive surgery, and the requirement of long pulses is especially important in the possible application to laser coronary angioplasty. A second use of long pulse lasers coupled with short cavity lengths, is in the attainment of narrow bandwidth oscillation. There is substantial gain in the degree of line narrowing per unit of dispersion as a function of the number of cavity round-trip times.[3] Long-pulsed, tunable narrow-bandwidth oscillators are extremely convenient injection sources for controlling the bandwidth, beam divergence, and polarization of power amplifiers[4]. Another use of long-pulsed excimer laser systems is the convenient generation of very short mode-locked pulses[5]. Such techniques may find applications in UV lidar as well as in continuum generation.

There are numerous approaches toward obtaining longer pulse lasing in excimer gases. They all attempt to prolong the time to streamer arc formation or to prolong the time when the discharge constricts to an arc due to nonuniformities in the ion-electron densities. Generically, they will be classified into three groups: 1.) Improvements based on changing the parameters of the discharge with small accompanying modifications in the pulse power set-up to take advantage of these improvements. 2.) Implementation of the pre-pulse concept as first discussed by Long, Plummer and Stappaerts[6]. And 3.) The use of stabilized electrodes first realized in resistively biased systems[7,8] and later in inductively stabilized systems[9].

Improvements based on present discharge systems

The most important thing one can do to improve the stable discharge time of the excimer gases is to improve the field uniformity of the discharge zone, to improve the preionization electron density uniformity and to increase the preionization number density.[10,11] These are important for all the classifications to be discussed. Preionization in discharge devices are generally accomplished using three methods: these are arc preionization, corona preionization and x-ray preionization. Arc and x-ray preionization can be very intense and corona and x-ray preionization can be made very uniform. Thus, only x-ray preionization delivers both benefits of possible high electron density as well as uniformity, but it adds substantial complication and cost as well as other issues concerning safety and long term reliability. Thus, the technique is not generally available in commercial systems although this will surely change in the near future. In addition, it should be mentioned that the stable discharge time of a device is proportional to the gap separation.

The first class of longer pulse operation devices are those where the preionization intensity or uniformity are improved. The gas mix is often made leaner in the hologen donor and in the heavier rare gas donor resulting in more stable discharges. Under these conditions the pulse power are modified to obtain longer laser pulses. Two specific examples of this are now given. A device at Marseille, France at the CNRS laboratory of the Institut de Mecanique des Fluides[12] uses x-ray preionization and a modified CLC transfer circuit. The peaking capacitors are made into a quasi-line with two roles of capacitors and an inductive element in between as shown in Fig.1 This has obvious limitations in that a true line cannot be built as the peaking capacitor system is pulse charged and capacitive elements further down the line cannot be charged to full voltage. However, such a system easily generate 80ns laser pulses. The second example is the work presented by NEC Corp.[13], where they put an inductive element between the peaking capacitors and the discharge electrodes (Fig. 2). By varying the inductive value they can vary the time period of the

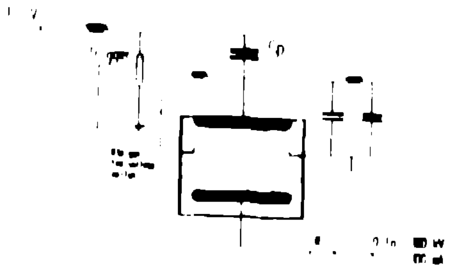


Figure 1. Electrical Schematic of Sentis, et al.[12]

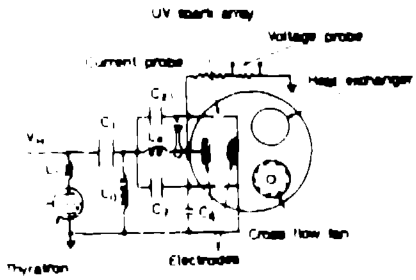


Figure 2. Electrical schematic of Itoh, et al.[13]

sinewave current pulse. This is extremely convenient in that it makes possible rapid pulse length variation by simply switching in and out inductive elements. (I believe the commercial Questek, Inc. long pulse XeCl system is based on this technique.) The problem with these techniques so far is that they tend to work effectively only for XeCl where the discharge tend to be substantially more stable than the fluoride based excimers.

<u>Lasers using the pre-pulse concept</u>

This technique uses a low energy, high voltage prepulse to breakdown the gas while the main energy is stored in a low voltage line set to two times the steady state discharge voltage. At this voltage setting the line impedance is equal to the discharge impedance and the power deposited is determined by the line impedance alone. Such a system avoids over voltage of the energy storage system in order to obtain gas breakdown and thus avoids the impedance mismatch that usually results in poor power transfer efficiency. In the initial[6] device (Fig.3) the low voltage storage line is isolated from the prepulse by a rail gap switch and when the prepulse circuit swings negative, the voltage across the switch is the difference between the two charging voltages resulting in multichannel breakdown of the isolation rail gap. 90% energy transfer efficiencies are possible using this concept giving impressive overall wall-plug efficiencies of better than 4 %. The operating pulse length is determined by the length of the low voltage energy storage line and is limited by the development of instabilities in the discharge. While this greatly improved the energy transfer efficiency, it in no way actively improved the discharge stability and the limitations to pulse length is still determined by the uniformity and rigorousness of the preionization, the field uniformity, the gas mix and the discharge gap separation. Further the use of a rail-gap for isolation, limits its

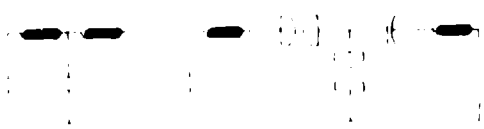


Figure 3. Pre-pulse concept using an isolation rail-gap. Long, et al.[6]

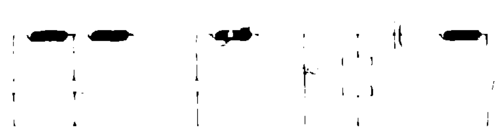


Figure 4. Pre-pulse concept with saturating inductor isolator as Fisher et al.[14]

general utility as a rep-ratable device. Thus, to make the technique commercially viable and high pulse repetition rate compatible, the concept of a saturating magnetic switch to replace the rail-gap has been invoked. We will now discuss this aspect of the pre-pulse system.

A saturating magnetic switch has been used to replace the rail-gap for isolating the prepulse from the low voltage energy storage line.[14,15] Such a system is given in Fig.4. The problem with the saturating magnetic switch for isolation is that the system needs peaking capacitors to work. This sets up a tank circuit that modulates the initial part of a long deposition pulse and depending on the value of the peaking capacitance needed, the modulated output can become unacceptable. The reason that the peaking capacitor is needed is due to the nature of the magnetic switching. At the same time that the prepulse reaches voltage to breakdown the gas it has also reverse biased that switch. This brings the switch down the hysterisis curve and possibly even to the point of reverse saturation. If reverse saturation occurs energy of the prepulse can be drained to the storage capacitors rather than used in breaking down the gas. However, the main problem is that the magnetic switch must now reach forward saturation before the switch opens so that energy from the low voltage storage line can be deposited into the gas. This usually takes a substantial amount of time (our experience is that this time is larger than 100ns) and by the time the switch forward saturates the high electron densities ($>10^{14}$/cc) in the discharge developed by the prepulse is already gone. Thus, to keep the electron densities up at steady state voltage values peaking capacitors are used to continue depositing energy into the gas until the switch saturates. It is possible to transformer couple in the prepulse on the same side as the low voltage storage line, Fig. 5, but this still reverse saturates the magnetic switch. One possibility is to feed back control the reverse saturation and keep the switch just below the forward saturation level so that little time is needed to reach saturation after the prepulse voltage drops to values to forward bias the magnetic switch.

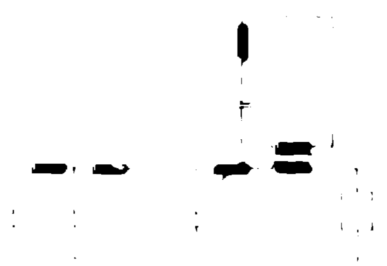


Figure 5. Prepulse scheme using transformer coupled prepulse.

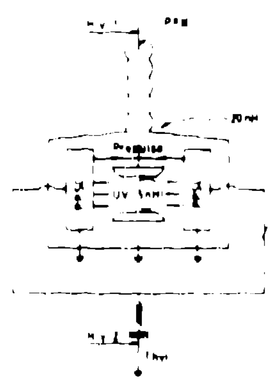


Figure 6. Pre-pulse scheme using inductive isolation as in Klopotek, et al. [16]

Certainly a number of commercial lasers based on the prepulse scheme now exists. The Lambda Physik[16] long pulse system uses differences in inductances to separate the prepulse from the low voltage storage line. A schematic of this is shown in Fig. 6. The laser from Advanced Interventional Systems Inc[2]. uses a transformer to couple the prepulse into the circuit with operating characteristics given in Fig.7. Again one reiterates that the prepulse scheme only provides an efficient means to couple long pulse energy into the discharge. How long the lasing pulse lasts still depends on the conditions mentioned; that of the degree and uniformity of the preionization, the uniformity of the electric field between the electrodes, the leanness of the gas mix and the electrode separation. Again for these reasons commercial systems are available only in the relatively stable gas mix of XeCl. A further disadvantage of the scheme is that, although transfer efficiencies are greatly increased with this scheme compared to the peaking capacitor charge transfer circuits commonly used in short pulse commercial laser systems, since the energy storage is at low voltage, the size of the capacitor goes up as the inverse of the voltage squared. This presently results in rather bulky storage systems.

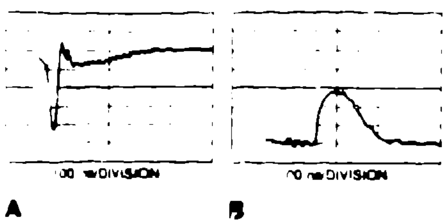


Figure 7.(A) Voltage and (B) lasing of the AIS, Inc. laser

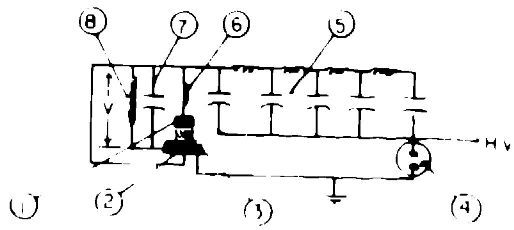


Figure8. Electrical schematic of a stabilized laser.

Discharge stabilizing electrodes

A technique has been developed where the discharge can be actively stabilized by the use of passive elements. This involves building a segmented electrode where each segment has a passive element (resistor or inductor) connected in series with the discharge segment. Inductive elements introduce little losses and is therefore the element of choice. The idea here is to introduce an increase in voltage drop across the stabilizing element with a corresponding decrease in voltage across the discharge element when there is a demand on the current due to the beginning of the formation of an arc. If an inductive element is used this is simply Ldi/dt. Experimentally it turns out that this inductance can be very small indeed. It has been shown that only a 5% change in the discharge gap voltage is sufficient to quench the streamer arc formation. Thus, the total inductance in an operating device of 28cm is only 3.5 nh and is small compared to the head inductance of some 5nh for this length. Therefore, the inclusion of the stabilizing electrode changes very little the overall parameters of the circuit. It is possible to incorporate the electrode into any of the circuits discussed previously to gain an added factor of stability. This gain in stability is most graphically illustrated in that now we can successfully operate long pulse lasers in XeF, KrF as well as XeCl. Thus, it is possible now to do a sloppier job on field uniformity, preionization density and uniformity and to be able to use very small discharge gaps and still obtain long laser pulses in all of the excimers mentioned above.

Along the spirit of taking advantage of this newly gained factor of stability, a very simple pulse power circuit is constructed and is shown in Fig. 8. This laser has been operated with a gap separation as short as 2.5mm. The performance characteristics for this 2.5mmX4mm cross-section discharge of 28cm gain length is shown in Figs. 9 and 10 for XeCl and KrF respectively. With the same energy storage, performance for a 1cmX1cm cross-section device is given in Figs. 11, 12, and 13 for XeCl, KrF and XeF respectively. 30 millijoules per pulse in XeCl and KrF are obtained with about 1/3rd this energy in XeF. Pulse lengths achieved varies according to the excimer system giving full width pulses as long as 150ns in XeCl to 70-80 ns pulses in XeF. Efficiency for the short gain length lasers are at 1% and is expected to improve to 3% given twice the gain length. This is shown in the output performance data of a modular laser of four gain sections (Fig.14) when firing them by adding more and more sections[17]. The reason for the initial large output energy gain is due to the fact that it takes two gain sections for the laser to reach saturation intensity.

This then is a simple solution toward improving the stability of an avalanche discharge system. The present devices has two limitations. First, is that it uses corona preionization. Since this form of preionization is very weak and only takes place during the rise of the voltage pulse and since the current now comes up rather slowly, some peaking current is needed to sustain the discharge from the initial preionization. Thus, a small amount of peaking capacitors are in the system (approximately 1/10th that of the storage capacitance) and this results in a modulation of the power deposition with similar modulation in the output lasing waveform. Figure 15 shows the output lasing waveforms of (a)an unstabilized laser of 4mm gap separationby 2mm wide discharge, (b)a 2.5mm gap separation by 4mm wide discharge stabilized laser and (c)a 10mmX10mm stabilized discharge. Of course, this can be easily solved by using other types of preionization as has been done on a system using x-ray preionization[18] where there is no modulation of the output lasing temporal profile. The second limitation is that the present segmented electrode uses epoxy although this is viewed simply as an engineering problem that can be solved with some effort.

Discussions

We have broken the discussion into three category of devices. The first two mainly are pulse power modifications to take advantage of the gain in discharge stability resulting from the uniformity improvements in the field and in the preionization as well as improvements in the strength of the preionization and the use of leaner gas mixtures. The inductive segmented electrode attempts to stabilize the discharge in an active manner. This appears to be quite effective in prolonging the discharge time to eventual streamer arc formations. However, we do not believe this will have much effect on the eventual constriction of the discharge due to avalanching from small local non-uniformities in charged particle densities. Thus, for very long stable discharges in the microsecond region very careful developments of uniform fields and preionization will be required.

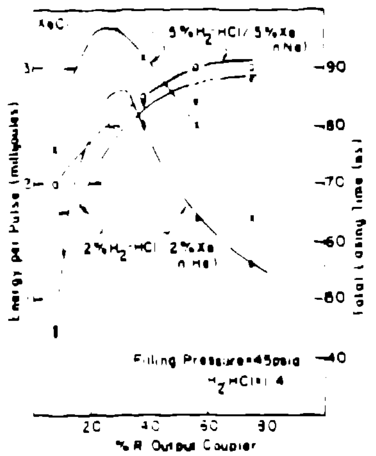


Figure 9. Lasing behavior as a function of output coupling in a 2.5mmX4mm x-section discharge in XeCl with He and Ne buffers.

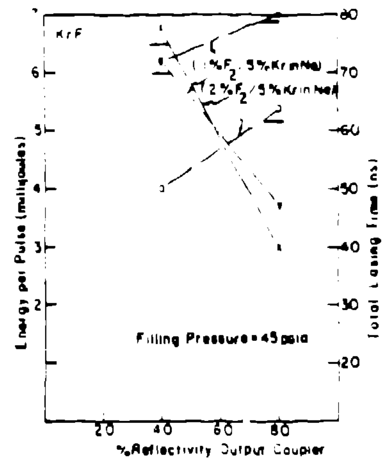


Figure 10. Lasing behavior as a function of output coupling in a 2.5mmX4mm x-section discharge in KrF with He and Ne buffers.

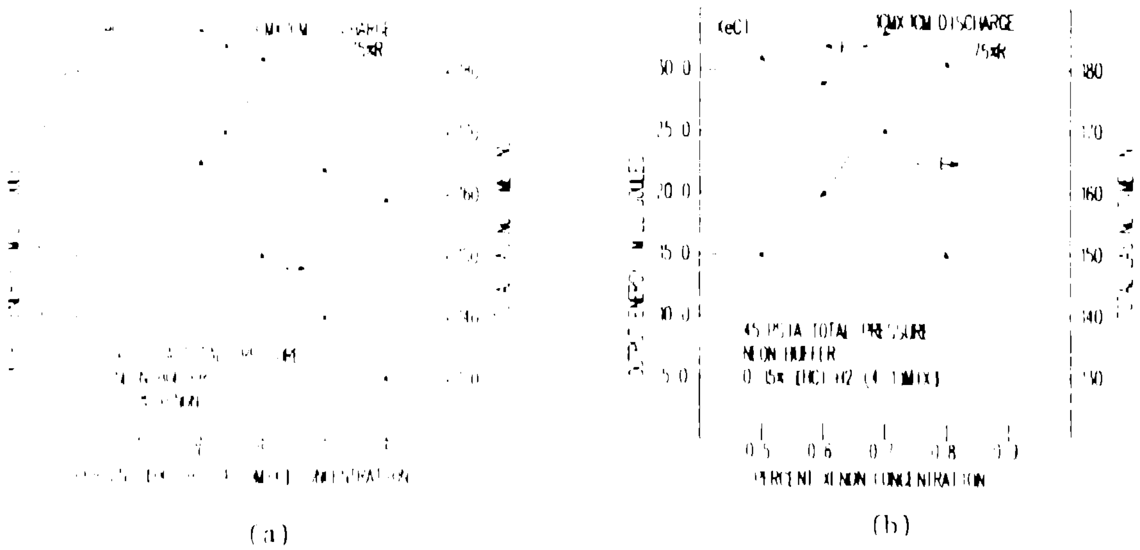
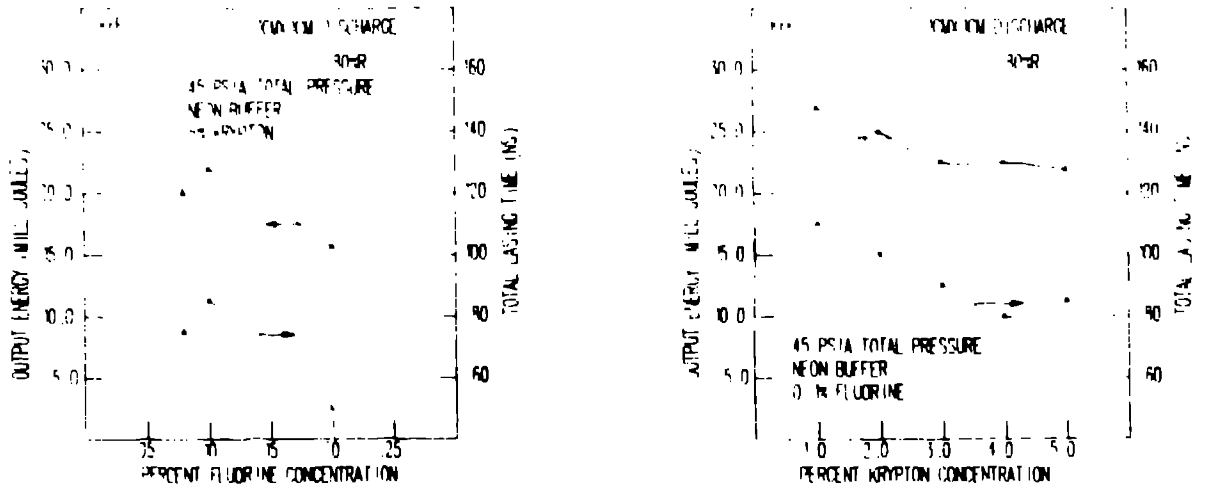
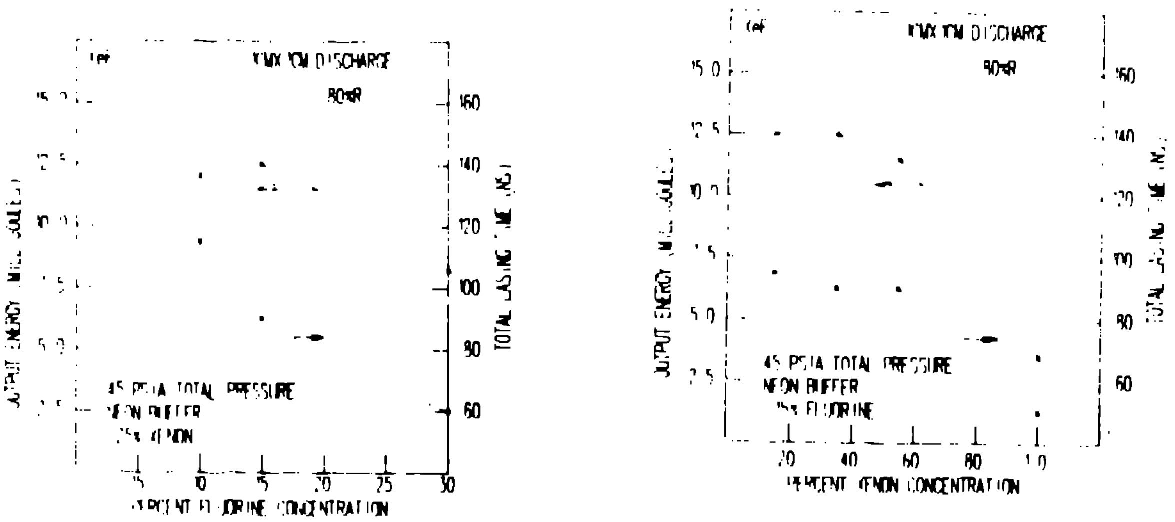


Figure 11. Lasing energy and total pulse length versus (a) $HCl-H_2$ concentration and (b) xenon concentration in XeCl in a 1cmX1cm x-section discharge.



(a) (b)

Figure 12. Lasing energy and total pulse length versus (a) F_2 concentration and (b) krypton concentration in KrF in a 1cmX1cm x-section discharge.



(a) (b)

Figure 13. Lasing energy and total pulse length versus (a) F_2 concentration and (b) xenon concentration in XeF in a 1cmX1cm x-section discharge.

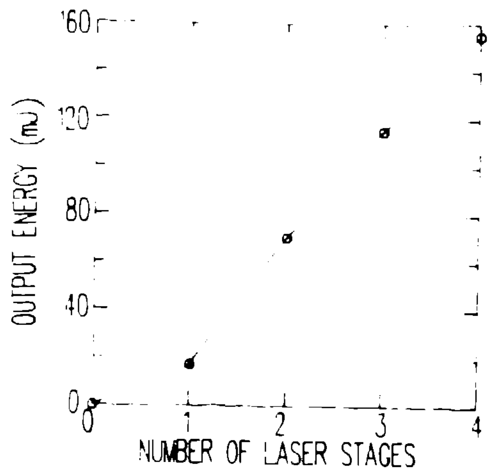


Figure 14. Lasing output as a function of gain stages fired in a 4 stage modular inductively stabilized laser.

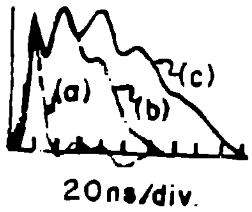


Figure 15. Temporal pulse shape of (a) an 4mmX2mm unstabilized discharge, (b) an 2.5mmX4mm stabilized discharge, and (c) an 10cmX10cm unstabilized discharge.

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